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RESEARCH MEMORANDUM

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RECENT EXPERIMENTAL FLUTTER STUDIES

By Arthur A. Regier and Dennis J. Martin

Langley Aeronautical Laboratory
Langley Field, Va.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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INTRODUCTION

The purpose of this paper is to present in a rather brief fashion some of the highlights of some recent experimental studies of flutter at high speeds. An attempt is made to bring together and compare the material of several papers; for some phases a more complete treatment will be found in references 1 to 16. In addition, some more recent research results are presented, but these results are preliminary in character and may therfore be subject to revision when a more complete analysis is available.

With the advent of transonic flight and the associated increase in importance of aeroelasticity, the flutter problems have become more varied. The flutter field has become very broad and has merged with several other aspects of aeroelasticity such as divergence, loss of control due to elastic deformation, dynamic stability, buffeting, and so forth. Although it is sometimes difficult to distinguish between flutter and other related problems it is important to do so because the corrective measures to be taken are, of course, different for the various phenomena. Flutter may be regarded as a self-excited oscillation of the structure involving an interaction between aerodynamic, elastic, and inertia forces and occurs when the damping of a vibration mode, or combination of modes, becomes negative. Such unstable oscillations may be mild or very destructive.

The subject of flutter may be divided into two broad categories. The first includes cases in which the flow is attached to the airfoil and is commonly called classical flutter. The second deals with flutter that is associated with flow separation and in this class is a type referred to as stall flutter. Buffeting, for example, is related to some extent to stall flutter and is generally thought of as the response of the structure to flow disturbances. For buffeting the problems are attacked by proper treatment of the external flow conditions

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while for flutter the cure may generally be achieved by internal treatment, that is, by changes in the magnitude and distribution of rigidity, damping, and mass of the structure. Some phases of the relation of the flutter field to that of dynamic stability will be discussed subsequently in this paper under the subject of flutter involving body modes.

The problem of flutter has been one of major concern to designers of practical aircraft in the past and will continue to be critical in the future. From a very simple consideration of two-dimensional supersonic flow, one might conclude that the flutter problem may be less acute for supersonic aircraft of the future. This conclusion is based on the assumption that on unswept wings flutter can generally be prevented by placing the airfoil-section center of gravity forward of the dynamic center of pressure. In two-dimensional supersonic flow the dynamic center of pressure is near the midchord, hence it should not be too difficult to design a wing having its center of gravity forward of the midchord, thus eliminating the flutter problem.

Unfortunately, the picture of flutter just presented is much too optimistic. The designers of practical transonic and supersonic aircraft of the future will probably still be plagued with the flutter problem.

One reason for this is that the use of sweepback and so forth to avoid the drag penalties of supersonic flow in the transonic speed range may inadvertently extend the subsonic flutter problem well into the supersonic speed range. Some experiments relating to this problem will be discussed later.

A second reason flutter may be an important consideration is related to the problem of whether strength or stiffness requirements determine the design of the airplane. Flutter depends on the stiffness and is independent of the strength. It is beyond the scope of this paper to discuss the effects that present design trends will have on the stiffness of future aircraft. However, when one considers the materials of construction it is found that much has been done to increase the strength of materials, but very little has been done to increase the rigidity.

A third reason flutter may be a serious transonic problem is that theoretical studies have indicated that wings of high mass ratio, that is, heavy wings at high altitudes, may be subject to a number of single-degree flutter troubles, particularly in the transonic speed range. (See reference 1; further research has been carried out relative to this problem and the results are being prepared for publication.) One type of flutter related to the single-degree flutter problem, namely, the bending-type flutter of swept wings, is discussed later.

As indicated by the title, this paper discusses a number of somewhat unrelated experimental investigations. The results presented should not be considered to give full coverage of the problem but rather to present representative samples. To avoid confusion, an outline of the material to be presented is given as follows:

TREND STUDIES FOR TRANSONIC SPEEDS
- Flutter of unswept wings
- Flutter of swept wings

STUDIES OF SPECIFIC PHENOMENA
- Bending-type flutter on swept wings
- Flutter involving body modes

PRELIMINARY STUDIES OF NEW CONFIGURATIONS
- Flutter characteristics of M and W wings
- Flutter characteristics of delta wings

The first subject dealing with trend studies for transonic speeds presents information for both unswept and swept wings. This work has been in progress for sime time and some of it has been discussed in other papers. (See references 2, 3, and 4.) This paper will present some of the latest findings.

The second subject deals with two studies of specific phenomena. The first is the single-degree bending-type flutter of heavy wings which showed up in some analytical studies and is now being investigated experimentally. The second is the low-frequency flutter involving body modes which was first observed experimentally on rocket vehicles carrying flutter models and is now being studied theoretically.

The third subject deals with preliminary studies of new configurations, namely, M, W, and delta configurations. This type of investigations serves a twofold purpose: It gives the investigator a quick qualitative indication of the nature of the problems associated with the phenomenon and it also serves as a guide to the flutter analyst, in that it may indicate the type of flutter and the significant modes of vibration that must be considered in the analysis.

TREND STUDIES FOR TRANSONIC SPEEDS

Flutter of unswept wings.- A comparison between some experimental flutter data with two-dimensional flutter theory is given in figure 1. The abscissa is the Mach number at which flutter occurred and the ordinate is the flutter-speed ratio. The flutter-speed ratio for the experimental points is obtained by dividing the experimental flutter speed by the flutter speed calculated for the test condition using a simple two-dimensional incompressible-flow theory. For the theoretical curve the flutter-speed ratio is the flutter speed calculated by compressible-flow theory divided by the flutter speed calculated by incompressible-flow theory.

The experimental curve in figure 1 for the NACA 65-009 wing is a composite curve and represents data obtained in the Langley 4.5-foot flutter research tunnel for subsonic speeds, by bomb-drop and rocket tests at transonic speeds, and from tests in the Langley supersonic flutter apparatus for the point at a Mach number of 1.3. (See references 2, 3, and 4.) The aspect ratios of these wings were approximately 7 and the section centers of gravity were located near the 45-percent-chord position.

It may be noted that the experimental curve is fairly flat at low Mach numbers and rises sharply at transonic speeds. This rise in the experimental curve is associated with the shift in the dynamic center of pressure associated with two-dimensional supersonic flow. For wings of different aspect ratio, center-of-gravity position, and so forth, the shape of the curve and its location may be quite different. For example, indications are that a rearward movement of the section center of gravity would make the turn-up of the curve occur at a higher Mach number. Also, the curve for lower aspect ratios should be considerably higher and flatter to higher Mach numbers than the curve presented in this figure. It may be of interest that in a recent rocket test a flutter failure occurred at a Mach number of about 2.0 on a fin having an aspect ratio of approximately 2 and a section center of gravity slightly behind the midchord.

To obtain some information on possible thickness effects on flutter at transonic speeds a series of bomb drops were made with some all-metal wings having a 4-percent root section and a 2-percent tip section with approximately the same center-of-gravity position, aspect ratio, and mass ratio ($1/\kappa$) as were used in the former tests. (See reference 5.) It may be noted in figure 1 that the curve through the data for the thin wing which is labeled NACA 65-002-4 agrees well with the thick wing at a Mach number of about 0.8, but near sonic speeds it lies somewhat below that of the thick wing. Such differences might be expected from a consideration of the differences in the local flow velocities for the two wings.

The theoretical curve is calculated by using linear theory, two-dimensional flow, zero thickness (reference 6), and shows reasonable agreement with experiment up to a Mach number of about 0.8. There is a rather fortuitous agreement at a Mach number of 1.0 and the deviations become larger at low-supersonic speeds. The theoretical velocity increases sharply at a Mach number of 1.3 and solutions are not obtained above a Mach number of about 1.4. The general shape of the theoretical curve envelopes the experimental data quite satisfactorily. It is known that, in the region of deviation at low-supersonic speeds, aspect-ratio effects are quite large and that taking account of the aspect ratio would probably result in better agreement between theory and experiment. (See reference 7.)

It may be noted that calculations are shown for a Mach number of 1.0. The use of linear two-dimensional theory for the zero-frequency or steady case leads to infinite air forces at sonic speeds. For the oscillatory condition the air forces, as given by the two-dimensional theory are finite and, as these experiments indicate, may have some usefulness. Tables of the oscillatory theoretical air forces at a Mach number of 1.0 are being prepared for publication. For further information on the theoretical oscillatory air forces at sonic speeds, references 8 and 9 are listed.

Before discussing some rocket tests which were made to determine the effects of Mach number on the flutter characteristics of swept wings, it is appropriate to present the flutter curves of figure 1 plotted in a different coordinate system. Such a presentation is useful to show the significance of the shape of the flutter curves with regard to design requirements and it is also useful for illustrating various testing techniques. The abscissa of figure 2 is the calculated incompressible flutter speed expressed as a Mach number, that is, the calculated two-dimensional incompressible flutter speed V_o divided by the speed of sound for the test condition. The ordinate is the experimental Mach number. If the flutter experiment agreed perfectly with incompressible-flow theory, the experimental curve would lie on the 45° line through the origin. This line is indicated in the figure. The experimental curve from figure 1 for the NACA 65-009, aspect-ratio-7 wing is replotted in figure 2 and labeled UNSWEPT. It may be noted that this curve follows the 45° line closely at low Mach numbers and then turns up and back at the higher Mach numbers.

For a particular configuration flying at a given altitude and temperature, the calculated flutter velocity and hence M_o has a fixed value. The flight history may be represented by a vertical line at that particular value of M_o. Flutter should not be encountered at Mach numbers below the intersection of this vertical line with the flutter curve. Consider the curve marked UNSWEPT. It may be noted that as the value of M_o is increased (for example, by increasing the wing rigidity) a value of M_o is reached beyond which no flutter is possible. Such a wing presumably would not encounter flutter at any Mach number.

The Mach number range over which flutter data may be obtained with various techniques may be determined from figure 2. For rocket techniques the flights are generally made at nearly constant density and temperature, and the flight line is essentially a vertical line. Thus rocket techniques are useful primarily for determining the lower part of the experimental curve, namely, the portion of the flutter curve that has a positive slope. In some recent rocket tests the models were not destroyed when they entered the flutter region and they continued fluttering as the Mach number increased. In such cases it may be possible to define some of the upper boundary of the flutter curve with rockets. By use of freely falling bodies it is possible to avoid the lower part of the flutter curve and to obtain data on the upper part in which the slope is negative. The reason for this is that, for a given wing, the value of M_o is quite high at high altitudes, and it progressively becomes less as the body falls to lower altitudes. The flight line of such a vehicle is a line which curves up and to the left, thus making a supersonic intersection with the flutter curve possible. In wind tunnels it is generally necessary to use special techniques to define the upper part of the flutter curve. (See reference 4.)

<u>Flutter of swept wings</u>.- The theory for the flutter of swept wings at transonic speeds, particularly for the low-aspect-ratio cases, has not been developed to the point where it may be conveniently used in engineering analysis. This is due to uncertainties with regard to both structural and aerodynamic considerations. With regard to the air forces, if the effect of sweep is to delay the transition to supersonic flow, one might expect that the flutter curves of figure 1 for highly swept wings would be moved to the right. Some supersonic-tunnel tests for long, highly swept wing models have indicated that this may be the case. (See reference 10.) An assumed curve in which the turn-back has been placed at a higher Mach number is presented in figure 2 and is labeled SWEPT. It may be noted that for such a curve the value of M_o necessary to avoid flutter would be greater. Sufficient data are not yet available to define such a curve accurately; however, data from some rocket tests with swept wings are presented to indicate some limits on such a curve for swept wings.

The configurations tested and the pertinent information are given in figure 3 for two series of sweptback wings which were tested by means of rockets. The information presented for the series designated NACA 65A009 is obtained from reference 11. The information for the series designated NACA 65A013 represents some recent data which have not been published as yet, and hence the information presented is tentative and subject to change in the final presentation. The value of M_o listed in the table is the calculated flutter Mach number, based on the use of incompressible two-dimensional air forces. The calculations were made by the method of reference 12. M_{FLUT} is the Mach number at which flutter started during the test. M_{MAX} is the maximum Mach number reached in the flight and is listed for those tests in which the model was not destroyed during flight.

The models for the first series of tests all had the same length and the same chord perpendicular to the leading edge. It was expected in this series that with increasing sweep angles the flutter speed would be progressively higher, following the same trend as the value of M_o. The model having zero sweep fluttered at the expected speed. (This flutter was a low-frequency type and is discussed subsequently.) The model having 30° sweepback fluttered at the expected speed and with a conventional bending-torsion flutter. However, what happened for the 45° and 60° sweep models was somewhat unexpected. Neither the 45° nor 60° models fluttered, even though the maximum speed reached was at a Mach number of 1.45. Noting the M_o for these wings, namely 0.74 and 1.01, it appears from an inspection of figure 2 that the flutter curve for these wings must be similar to that given for the unswept wing, since no intersection was obtained with the flutter curve, even though the flight line extended to a Mach number of 1.45. The tentative conclusion to be drawn from these tests is that sweepback for the wings of this aspect ratio did not extend the flutter curve to higher values of M_o as was indicated by the assumed SWEPT curve in figure 2.

In order to explore further the transonic flutter curve for swept wings, two more configurations of higher aspect ratio were tested. These wings are similar to some that might be considered for high-speed bombers and are designated in figure 3 as NACA 65A013 perpendicular to the quarter-chord line. The aspect ratio of the 45° swept wing of the second series is about double that of the first. If a comparison is made between the calculated and experimental flutter speeds of the 45° swept wings of the first and second series, it may be noted that the first wing did not experience flutter up to the maximum Mach number of the test, $M = 1.45$, although the calculated M_o was 0.74. This indicates that the flutter curve for this wing has turned up below a Mach number of 0.74. The calculated M_o for the second wing was 0.87 and flutter was obtained at a Mach number of 0.89. The wing continued to flutter up to the maximum speed of the test, $M = 1.17$. This indicates that the flutter curve for the wing has not turned up appreciably at a Mach number of 0.87. Similarly, a comparison for the 60° wings indicates that the flutter curve must extend to higher values of M_o for the wing of higher aspect ratio.

A study of the flight record of the high-aspect-ratio 60° wing indicates that the wing started fluttering at a Mach number of approximately 1.09 and was still fluttering at the maximum speed of the missile, which was at a Mach number of 1.52. The amplitude of the oscillation increased to approximately 20° torsional oscillation at a Mach number of 1.2 and decreased in amplitude at the higher Mach numbers. On the deceleration part of the flight the pattern was repeated in reverse, the same amplitudes occurring at approximately the same Mach numbers. Although there are not sufficient data to determine the flutter curve for this wing, the curve in figure 2 marked SWEPT might serve as an estimate.

It may also be noted that the agreement between the experiment and incompressible-flow theory is quite good for the high-aspect-ratio 60° wing even though the flutter occurred at supersonic speeds. The indications are that the normal flow concepts for swept wings may be valid at transonic speeds, provided that the aspect ratio is sufficiently high.

STUDIES OF SPECIFIC PHENOMENA

Bending-type flutter on swept wings.- The flutter that has been discussed thus far has been predominantly a coupled, bending-torsion flutter in which the phenomena are strongly dependent upon the torsional properties of the wing. Also important to the airplane designer is an understanding of certain phenomena in which the flutter is dependent upon the bending properties of the wing. One such phenomenon is a bending-type flutter of swept wings which first appeared in the analysis of heavy, low-aspect-ratio wings. This instability is closely related to the single-degree bending-type flutter reported in reference 1.

A theoretical analysis has recently been made, based on reference 12 using two-dimensional compressible air forces, of the flutter trends of two similar 45° swept wings which differed primarily in the mass-ratio parameter $1/\kappa$. In order to illustrate this bending-type flutter the results of this analysis are presented in figure 4. Shown in this figure as an ordinate is the velocity ratio V/V_o, flutter speed calculated by the simple two-dimensional theory using compressible-flow coefficients normalized by dividing by the speed calculated by using incompressible-flow theory. This velocity ratio is plotted against the Mach number normal to the leading edge M_N although the choice as to the use of normal or stream Mach number for low-aspect-ratio wings has not been established as yet.

The parameters that are significant to this type of flutter are listed in the table. They are the sweep angle Λ, the length to chord ratio l/c (the chord is measured perpendicular to the leading edge), the mass-ratio parameter $1/\kappa$, and the frequency ratio ω_h/ω_α. It can be seen that wing B has about 4 times as large a mass-ratio parameter $1/\kappa$ as wing A and may be considered as a heavier wing than A at the same altitude, or, these wing may be looked upon as being wings of equal weight at different altitudes, the higher altitude being represented by wing B. The dashed curve represents the flutter boundary for wing A and is characterized throughout by a conventional bending-torsion type of flutter. The solid curve for the heavier wing, or the wing at higher altitudes, shows a somewhat drastic reduction in flutter speed with increasing Mach number up to supersonic speeds. In addition, the type of flutter changed to a bending-type flutter at the higher Mach numbers and the flutter frequency was approximately the bending frequency of the wing.

To the airplane designer the results of these theoretical studies are somewhat discouraging because they illustrate a type of flutter which may be very troublesome at transonic speeds. To the flutter analyst this is somewhat disconcerting because it indicates that, although in the past it has been very convenient to estimate flutter speeds by making calculations based upon incompressible-flow theory and then applying a compressibility correction, now it is indicated that the compressibility correction for this type of instability depends sharply upon certain parameters of the model.

Experimental investigations are being made of this phenomenon and preliminary results indicate that the damping in the bending degree of freedom for swept wings suffers a drastic reduction as sonic speeds are approached.

Flutter involving body modes.- The significance of free-body modes on flutter has been of interest for some time. (See references 13 and 14.) In some flutter tests on unswept wings made by use of rocket vehicles at Langley, a low-frequency flutter was encountered. This flutter occurred at a frequency below the first bending frequency of the wing and near the frequency of the short-period oscillations of the body. An analysis of this type of flutter has been made in reference 15 and some of the results are presented in figure 5. The ordinate is the flutter-speed coefficient, $V/b\omega_h$, in which it may be noticed that the bending frequency ω_h is used, since for this type of flutter the wing bending frequency is a significant parameter. The abscissa is the nondimensional distance of the wing behind the center of gravity of the body, in terms of wing chord.

Four degrees of freedom were used in the analysis, namely, two body modes, that is, pitching and translation, and two wing modes, primary wing bending and wing torsion. Two branches of the flutter curve are shown in figure 5. One branch of the curve represents the conventional bending-torsion flutter and it may be seen that this branch is essentially independent of the position of the wing on the body x/c. The other branch is the low-frequency flutter branch which involves primarily body pitching and wing bending. This mode is strongly dependent on the wing location x/c. The flutter speed for this type of flutter is much lower than for the bending-torsion flutter for rearward positions of the wing and its value is higher than the bending-torsion flutter for forward positions of the wing. An experimental point is shown for the model used in this analysis. The agreement between experiment and theory is considered satisfactory both with regard to the flutter speed and the flutter frequency.

The above analysis has been made by use of the theoretical air forces for the oscillating airfoil in two-dimensional incompressible flow. An analysis of some (as yet unpublished) preliminary tests made with pitching models in the Langley 4.5-foot flutter research tunnel indicates that some improvement in the agreement between theory and experiment may be obtained by taking account of the aspect-ratio effect. It appears that for the low Mach number range, the quasi-steady air forces may be of some value in predicting such low-frequency flutter phenomena. However, the significant conclusion that can be drawn from the studies of pitch-bending flutter that have been discussed is that the most important consideration is the inclusion of the proper degrees of freedom in the analysis.

It may be recalled that, in the discussion of the unswept wing of the NACA 65A009 series of figure 3, the flutter obtained for this model was at about the right speed but of a low-frequency type. For this model the leading edge of the test wing was mounted near the center of gravity of the rocket model and the oscillograph records of the test indicated that the model encountered the pitch-bending type of flutter. The flutter curves of figure 5 are close together in the region of x/c near zero and hence indicate that it was reasonable for the unswept wing of figure 3 to flutter at about the expected speed but in a different mode than was expected, since body modes were not included in the preliminary analysis.

PRELIMINARY STUDIES OF NEW CONFIGURATIONS

Flutter characteristics of M and W wings.- As was mentioned earlier, some preliminary studies have been made that were designed to furnish the flutter analyst with a quick evaluation of the problems inherent with new configurations and to provide an indication of the significant modes. The results of one such investigation by Robert W. Herr, which are being prepared for publication, on M and W wing plan forms are presented in figure 6. Shown here is the indicated airspeed IAS at which flutter was obtained on M and W wings of similar rib and spar construction. The tunnel density was varied and the flutter speeds are plotted here as a function of altitude. The mass-ratio parameters $1/\kappa$ are indicated for several altitudes. The frequency spectrums for both wings are given and the flutter frequency f_f of about 10 cycles per second throughtout the altitude range for both models indicates that there were no mode changes with varying density and that the flutter encountered was a fairly clean type involving the first two modes. The wings of these experiments each had a single spar of constant diameter. Diederich and Foss have shown in an unpublished paper that stiffness distribution, geometry, and so forth may materially alter the characteristics of wings of this type and, although the stiffness distribution was not too realistic for these wings, the W wing appeared considerably better than the M wing with regard to flutter. Other experiments on flat-plate models have indicated that an equivalent swept wing would exhibit flutter characteristics slightly better than the M wing and considerably below the W wing.

Flutter characteristics of delta wings.- Previously the possibility of flutter on delta wings has not been considered likely. Recently, however, flutter was obtained at low-supersonic speeds on a rocket model carrying 60° delta wings. (See reference 16.) This flutter occurred at a relatively high frequency and was of sufficient intensity to produce failure in a rather sturdy model. Further tests have been carried out in the Langley 4.5-foot flutter research tunnel on a series of 45° and 60° delta wings. The wings used in these experiments were constructed of balsa wood which was glued to an aluminum insert and shaped to an NACA 16-004 airfoil section in the stream direction. During the flutter of these wings the weak tip section experienced large-amplitude oscillations and the effect of cutting off this weak tip section was investigated. The results of these investigations are shown in figure 7 for 45° delta wings. The indicated airspeed at which flutter occurred is plotted against the density of the test medium expressed in terms of altitude. The mass-ratio parameters $1/\kappa$ are listed at several altitudes. The unmodified delta flutter speeds are shown by the circles and the flutter frequencies are indicated above this curve. At the low altitudes or high densities the flutter occurred at a frequency of about 46 cycles per second. At the intermediate altitudes the flutter occurred at a frequency of about 98 cycles per second and at the high altitudes the flutter frequency was about 66 cycles per second. These sharp changes in flutter frequency and indicated airspeed indicate a change in the flutter mode as the air density was changed. The wing was modified to determine the effect of cutting off first 3 and then 6 inches of the weak tip section and it was found that removing the weak tip section had a very beneficial effect at sea-level density. At higher altitudes, however, the effect of removing the weak tip sections presents a very confused picture. From an examination of the frequency spectrum for the vibration modes and a consideration of the chordwise bending or camber mode which had a natural frequency of about 120 cycles per second, it can be seen that the flutter which occurred involved many of the higher modes of vibration. The indications are, then, that many of the higher modes of vibration must be included in a flutter analysis of delta wings.

CONCLUDING REMARKS

In conclusion it may be stated that for nominal to high aspect ratio the agreement between theory and experiment is satisfactory. High-aspect-ratio wings of high sweep angles will probably be subject to flutter troubles at supersonic speeds much as they have been for subsonic speeds.

For the low-aspect-ratio configurations the flutter problem may not be acute; however, there are still too many unknowns in the problem to warrant any general conclusions at this time.

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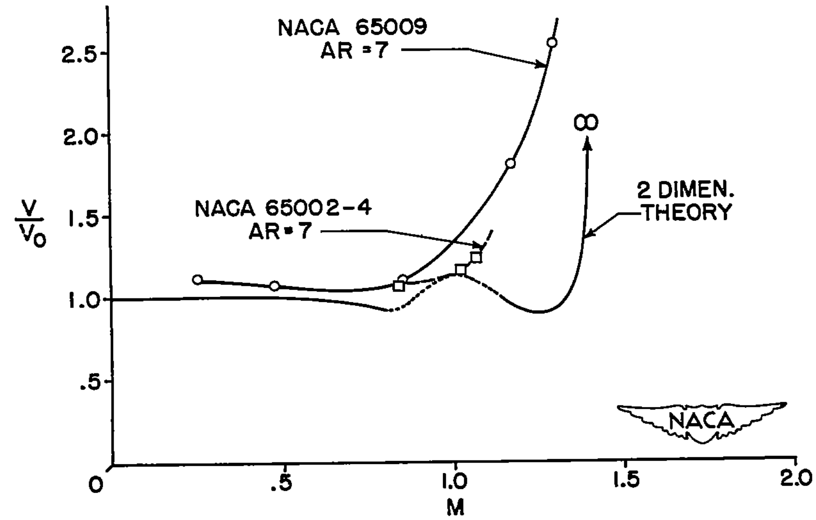


Figure 1.- Trend studies of unswept wings at transonic speeds.

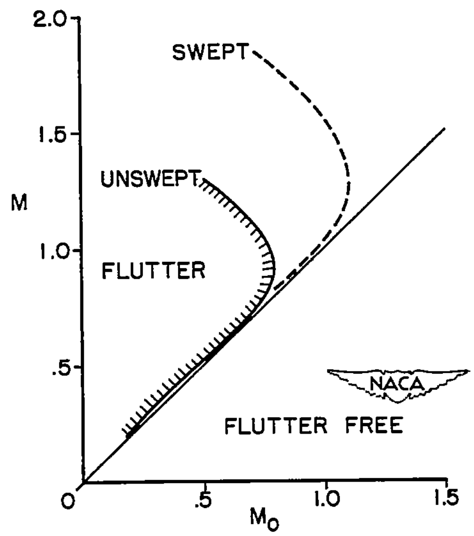
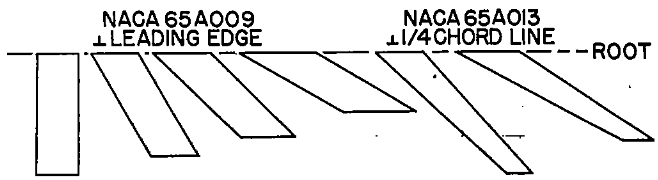


Figure 2.- Trend study chart of swept and unswept wings at transonic speeds.



SWEEP	0°	30°	45°	60°	45°	60°
AR	7.3	5.6	3.9	2.1	8.1	4.3
M_O	.66	.70	.74	1.01	.87	1.06
$M_{FLUT.}$	.70	.78	NO	NO	.89	1.09
M_{MAX}	—	—	1.45	1.45	1.17	1.52

ROCKET TESTS

Figure 3.- Trend studies of swept wings at transonic speeds.

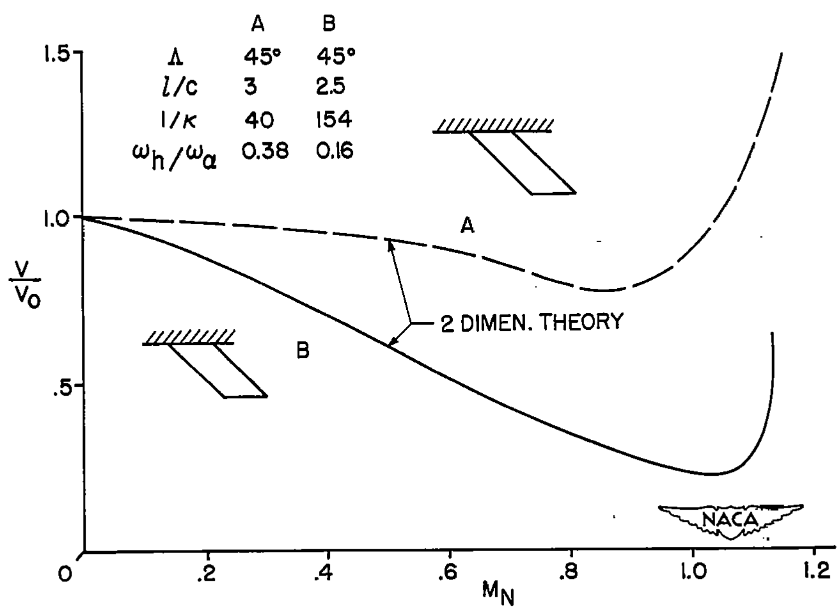


Figure 4.- Theoretical study of bending-type flutter on swept wings.

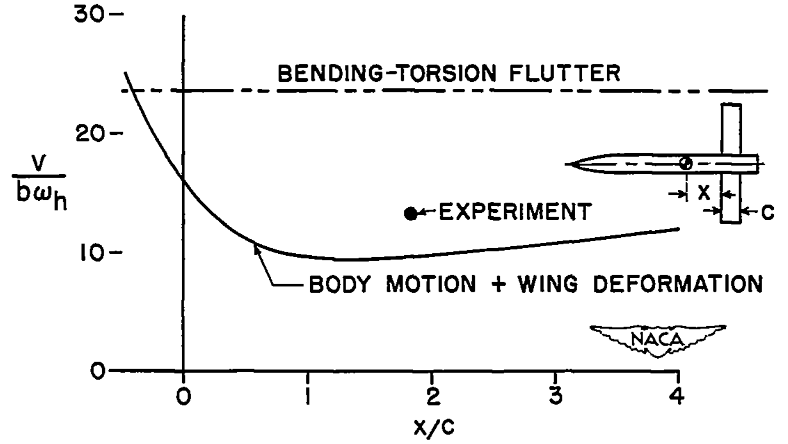


Figure 5.- Theoretical study of flutter involving body modes and comparison with experiment.

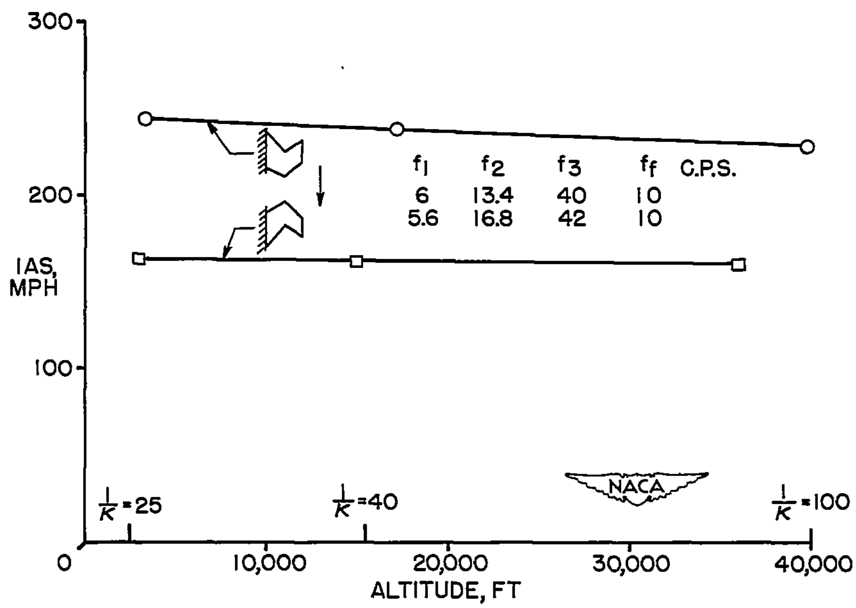


Figure 6.- Flutter characteristics of M and W wings.

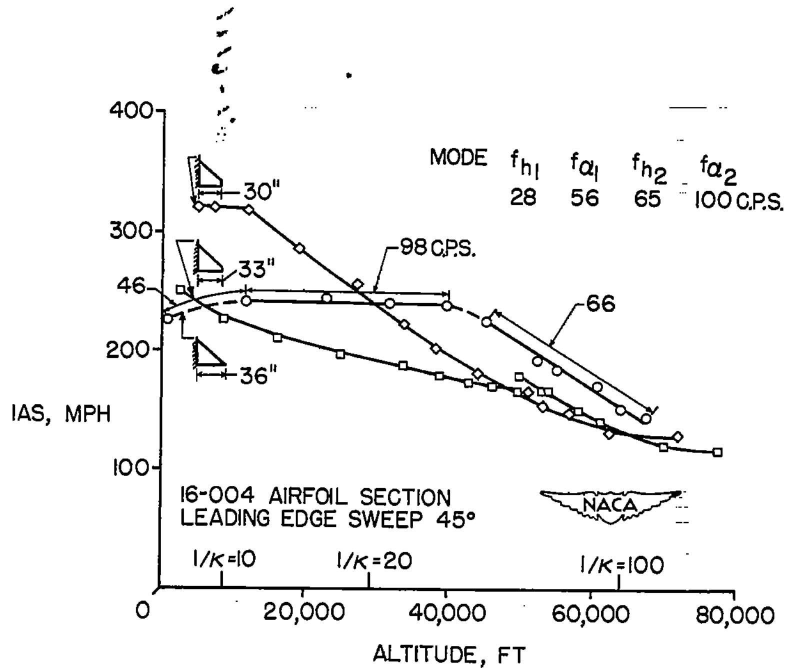


Figure 7.- Flutter characteristics of delta wings.